Innovative Approaches for Sustainable Utilization of Scrap Tires

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1. Abstract:

The global challenge of disposing of over one billion end-of-life tires annually. It advocates for circular economy principles, emphasizing reduction, reuse, recycling, and recovery. As a non-biodegradable material, extra care is required to eliminate the environmental impacts associated with the tires. Exploring strategies like product redesign and pyrolysis recycling, the research underscores the need for a comprehensive approach across the tire value chain. It emphasizes the importance of technological advancements, policy incentives, and public awareness for sustainable scrap tire management. Implementing circular solutions can minimize environmental impact, create economic opportunities, and fully utilize tire resources for long-term sustainability.

2. Introduction

This research paper delves into the urgent issue of scrap tire management, investigating innovative approaches to sustainable utilization. Scrap tires, which number in the billions each year, present significant environmental and health hazards due to their resistance to degradation and chemical composition (Oboirien & North, 2017). With over 290 million tires discarded annually in the United States alone, the magnitude of this problem is staggering (Federal Highway Administration, 2022). Proper disposal and recycling of scrap tires is crucial to prevent public health risks, minimize environmental impacts, and enable a transition to circular economic practices. This paper aims to underscore the necessity for a circular economic approach to tackle the scrap tire problem effectively. It explores strategies across the tire lifecycle, from production redesign to end-of-life recovery and recycling, that can transform tires from an environmental burden to a valuable material resource. By applying principles of reduce, reuse, recycle, and recover, known as the 7 Rs, it is possible to maximize resource utilization and eliminate waste (Araujo-Morera et al., 2021). The research also investigates policy frameworks, economic incentives, technologies, and public awareness efforts that must work in tandem to drive the transition towards sustainable scrap tire management. Ultimately, this paper seeks to demonstrate that, through comprehensive lifecycle assessments and environmentally conscious innovations across the value chain, the scrap tire challenge can be leveraged to advance both sustainability goals and economic growth. With circular economy solutions, tires can be continually cycled to capture their embedded energy and material value.

3. Literature Review

3.1 Composition of Tires

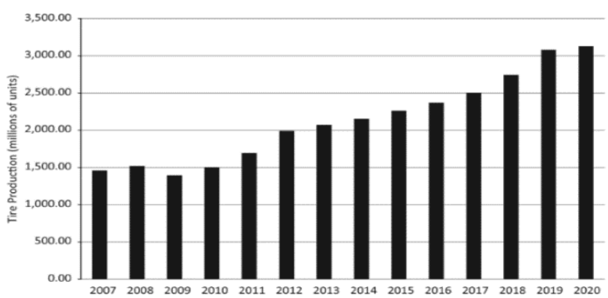
According to the Brendan Rodgers and Walter Waddell "In human history, the wheel is considered one of the most important inventions, because it found use in a wide range of applications such as transportation vehicles, construction equipment, and internal parts of machinery. The discovery of vulcanization by Charles Goodyear in 1839 and the industrialization of Europe and North America enabled the tire to evolve from a rubberized canvas covering a rubber tube to a complex fabric, steel, and elastomeric composite. In terms of both volume production and consumer awareness, pneumatic tires fall into essentially nine categories, based on vehicle application. There are tires for racing vehicles, passenger vehicles, and light trucks where gross vehicle weights typically do not exceed 7250 kg." Tires are essential for mobility, and fundamental for the safety of vehicles. They perform numerous functions: bear the weight of the vehicle, transferring the load to the surface; provide grip between the vehicle and the road for braking and acceleration; and act as vibration absorbers, enhancing road comfort and safety and improving the overall performance of the vehicle (The International Market Analysis Research and Consulting Group - IMARC Group, 2020). According to Valerie L. Shulman "No matter where the tire is produced, all tires contain four fundamental material groups: natural and or synthetic rubbers, carbon blacks/silicas, reinforcing material (metals/textiles), and facilitators(sulfur, zinc oxide, stearic acid, Extender oils, waxes, plasticizers, peroxide, and accelerating agents; Antioxidants, antiozonants, and so on)."According to World Business Council for Sustainable Development "A typical passenger tire contains 30 types of synthetic rubber, eight types of natural rubber, eight types of carbon black, steel cord, polyester, nylon, steel bead wire, silica and 40 different kinds of chemicals, waxes, oils and pigments. Tires typically contain 85% hydrocarbon, 10-15% iron (in the bead wire and steel belts) and a variety of chemical components." A tire is manufactured from a variety of materials, including several rubber components, each of which provides a specific and unique purpose. Natural rubber (NR) is used in tire casings requiring high durability, while synthetic

rubbers are used in tread materials to provide tire grip. Chemicals (expressed in parts per hundred rubber – phr) serve as antioxidants, curatives, and processing aids; carbon black (CB) and silica are added as reinforcing agents; and cords composed of textile, fiberglass, and steel wire (brass, bronze or zinc plated) provide stability and stiffness. About three quarters of the tire corresponds to the rubbery compound, which includes the polymer, fillers, and chemicals. The composition in weight percentage of raw materials varies depending on the tire type. These materials are selected based on their mechanical and physical characteristics and on their interactions with other constituent materials, providing a broad range of properties (Anderbilt et al., 2010).

Material	Car/Utility (%)	Truck/Bus (%)
Rubber/elastomers[a]	48	45
Carbon black/silica	22	22
Metals	15	25
Textiles	+5	–
Zinc oxide	1	2
Sulfur	1	1
Additives	8	5

[a] *Natural/synthetic rubber ratio "truck tires ±1–2 car tires ±3–4.*

Table 1: showing the composition by mass by Car and truck (source: Tire Engineering: An Introduction by Brendan Rodgers)



Graph 1: showing the production from 2007-2020 (source: Tire Engineering: An Introduction by Brendan Rodgers)

TABLE 1.1
Global Tire Manufacturing Participation and Revenues (7, 8)

America	Europe	South Asia	North Asia	Company	Revenue (billions $)
Goodyear Tire	Continental	Apollo	Bridgestone	Bridgestone	27.22
Cooper Tire	Michelin	Ceat	Cheng Shin	Michelin	25.40
Titan	Nokian	JK Tyre	Hankook	Goodyear	15.37
	Pirelli	MRF	Kumho	Continental	13.11
		GiTi	Linglong	Sumitomo	6.81
			Nexen	Pirelli	6.15
			Sailun	Hankook	6.12
			Sumitomo	Zhongce	4.80
			Toyo	Yokohama	4.14
			Yokohama	Cheng Shin	3.74
			Zhongce	MRF	3.50
				Toyo	2.95
				Cooper	2.85
				Apollo	2.17

Table 1.1: showing the global tire manufacturers (source: Tire Engineering: An Introduction by Brendan Rodgers)

3.2 Waste Tire/ End of life tire/ scrap tire

According to World Business Council for Sustainable Development "A tire is considered at the end of its life when it can no longer be used on vehicles (after having been retreaded or regrooved). All tires including passenger cars, truck, airplane, two-wheel and off-road tires result in ELTs. However, the bulk of ELTs result from car and truck tires." A tire can reach the end of its on-road life at various points after production and initiation on the road. Once permanently removed from a vehicle with no possibility of being returned to the road, the tire is considered a "waste."

3.3 Consequences of Neglecting Scrap Tire Recycling

Scrap tires contain valuable materials that could be reused or recycled. Failing to recycle them results in the loss of these resources and perpetuates a linear, unsustainable approach to tire consumption.

3.3.1. Landfill and waste piles:

According to C. Sathiskumar, S. Karthikeyan "The annual generation of waste tires throughout the world is estimated to be about 4 billion tons.". According to Valerie L. Shulman "In 2016 about 3.2*10^{6}t, (3,200,000 t) of tires were classified as waste in the EU, with comparable quantities arising in North America and also in Asia." According to World Business Council for Sustainable Development "Globally, an estimated one billion tires reach the end of their useful lives every year." An estimated 4 billion ELTs are currently in landfills and stockpiles worldwide. According to the World Business Council for Sustainable Development "Another major issue in managing ELT stockpiles is developing an accurate assessment of the actual number of ELTs in stockpiles. This is called stockpile mapping and has been undertaken in the USA, for example using satellite imagery. It is estimated that there are more than a billion passenger vehicles in the world. Imagine the number of tires that will be eventually disposed of." According to a Federal Highway Administration Research and Technology report, "In the United States alone, approximately 280+ million used tires are discarded each year. Only about 30

million of these tires are retreaded or reused, leaving the remaining 250 million scrap tires to be managed." The magnitude of the scrap tire problem is staggering. It takes approximately 50-80 years (or longer) for a tire to completely decompose in a landfill. So, with 290 million being discarded every year, the landfill would quickly become overrun with old, unusable tires. Another issue is space. Tires aren't small and whole tires take up a lot of space in landfills. Their hollow, rounded shape takes up valuable shape in landfills. Additionally, tires often don't stay buried. They have the unfortunate habit of trapping gases like methane and then "bubbling up" through landfills. According to World Business Council for Sustainable Development "South Africa is currently faced with an estimated 800 million tires in piles in the Western Cape region. In Mexico the number of tires is thought to be around 1-2 billion." According to Ningbo Gao , Fengchao Wang, Cui Quan, Laura Santamaria, Gartzen Lopez, Paul T. Williams "The treatment and disposal methods applied to waste tires in some countries also includes disposal in waste landfill. However, waste tires do not readily degrade in landfills because of the presence of strong cross-linking of sulfur bonds and rubber in the tire rubber formulation. Therefore, there is a recent impetus to find more sustainable and higher value resource-recovery options for the treatment of waste tires."

3.3.2. Fire Hazards:
According to Kurt Reschner "The most obvious hazard associated with the uncontrolled disposal and accumulation of large amounts of tires outdoors is the potential for large fires which are extremely detrimental to the environment. Once a large pile catches fire, it is very hard, if not impossible, to extinguish. Also, air and soil pollution are even worse if attempts are made to extinguish the fire with foam or water." Accumulated scrap tire piles are highly flammable, posing a risk of uncontrolled fires. When ignited, these fires release toxic chemicals into the air, contributing to air pollution.

3.3.3. Vector for Disease:
Tire stockpiles provide shelter for rodents and become breeding grounds for disease-carrying insects, particularly mosquitoes. tires are thick enough to provide insulation and protection for the eggs of mosquitoes. It is not surprising, therefore, that those insects love to breed in old tires. According to the Beach and Schroeder, 2000 "The stagnant water collected within tire piles creates an ideal environment for mosquito larvae, increasing the risk of diseases like West Nile virus, Dengue fever, Yellow Fever, Malaria, Zika virus and the list of mosquito-borne diseases is long. Rodents, in particular, can transmit diseases such as leptospirosis, salmonellosis, rat-bite fever, and other Rickettsial diseases." According to the Kurt Reschner "Even if large outside tire piles do not catch fire, they still pose a serious problem for human health and the environment: Disease carrying mosquitoes, find an ideal breeding ground in the countless little puddles which form in virtually each tire as it rains. Especially in areas with warmer climates mosquito-borne diseases like encephalitis and dengue fever have been reported around large tire piles."

3.3.4. Aesthetic and Environmental Degradation:
According to the World Business Council for Sustainable Development "Fire and infestation risks can largely be overcome (at extra cost) if tires are shredded and/or buried. However, by doing this, potentially valuable usable resources still become unnecessary waste. Additionally, buried whole tires can often rise to the surface or "float" and reduce the future usability of a site." Abandoned tires in open spaces contribute to environmental degradation, impacting the visual appeal of landscapes. Moreover, they can leach harmful chemicals into the soil, affecting the surrounding ecosystem.

3.4 Transitioning to Circular Economy Practices

According to Javier Araujo-Morera, Raquel Verdejo, Miguel Angel López-Manchado, Marianella Hernández Santana "The linear economy model of "extract-manufacture-consume-dispose" has prevailed for decades, but it is increasingly recognized as unsustainable and detrimental to the environment The traditional disposal approach involves stockpiling, landfills, or, in the worst cases, illegal dumping. However, these methods are not only inefficient but also highly detrimental to the environment. there has been a paradigm shift from the linear economy model to the circular economy (CE) model. The CE model replaces the idea of "disposability" with "restoration." It aims to minimize waste, maximize resource utilization, and promote long-term sustainability.

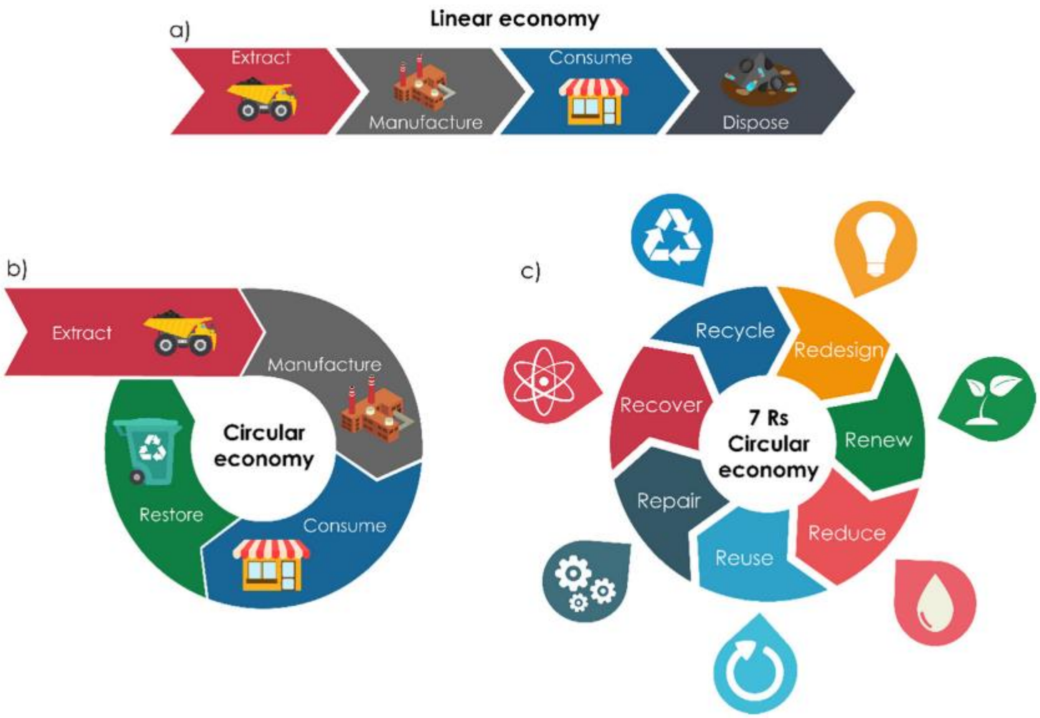


Fig. 1. a) Linear and b) circular economy models. c) 7Rs of the circular economy model.

Source: Javier Araujo-Morera, Raquel Verdejo, Miguel Angel López-Manchado, Marianella Hernández Santana

3.4.1. Redesign:

The proposed tire redesign and recycling process improvements contribute to an enhanced circular economy for tire products. According to the S.M Samindi M.K Samarakoon, Pal Rubena Jorgen Wie Pedersen, Luis Evangelista "In recent years, specific objectives in the field of environmental protection, namely minimizing waste, increasing recycling rates, or increasing product lifetimes, have become fundamental components of sustainable development strategies. However, it is obvious that their simple enunciation, without transposition into reality, is not enough. To achieve these goals, it is necessary to develop so-called green engineering, which should focus on designing and delivering products using sustainable methods based on science and technology." An important issue that should be taken into consideration when designing products is the possibility of more easily separating the materials of which they are made. This category of products also includes tires that have a rubber matrix, a metal insert, and a textile insert. The separation of tire components involves large amounts of energy and materials, but also quite complex technological processes [According to the Shulman, V.]. Thus, certain known separation methods involve the use of large quantities of hazardous solvents, while other methods are based on high energy consumption in the form of heat or pressure. Under these conditions, it is advisable to design products that allow either the separation of components or the substantial reduction of energy consumption. A tire design strategy can be adopted to enable products to be produced using components with desirable properties but to allow easy separation during the recovery process.

According to the ETRMA—ETRMA-European Tire & Rubber Manufacturers' Association "Waste recycling has become an extremely important issue in regards to registering a larger quantity of waste due to its negative impacts on the environment. At present, waste in the form of used tires has become a real threat due to environmental pollution (satellite images of the Kuwait desert with black spots are relevant, which shows the world's largest landfill, containing over 7 million used tires) but also due to their effects on the health of the population (the incineration of rubber waste causes the release of large amounts of gas into the atmosphere)." According to the ETRMA—ETRMA-European Tire & Rubber Manufacturers' Association "Currently at the EU level, due to the problems of separating the three ingredients from the total waste

collected, 58% of tires are recycled, 48% are used as a fuel source (75% in the cement industry and 25% in other industries) and 5% remain as residual waste.”

According to the ETRMA—ETRMA-European Tire & Rubber Manufacturers’ Association “Applying this new scenario has some limitations on tire design at the current time. This also results from the fact that the environmental footprint of a product is determined from the design phase of the product. Lately, in the tire industry, the design of lighter, more fuel efficient, and more durable tires has been considered, using less resources for the same tire performance. However, this approach is not enough because designing the tires has not yet accounted for ensuring easy recycling. There are on the market tires with several inscriptions on the side surface, including the type of materials used (rubber, steel, nylon, etc.). However, this type of inscription is one that does not help much in the future tire recycling process. Thus, certain constructive modifications of the tires or their material should be carried out at the design stage. In this respect, it would be necessary to have either inscriptions or a series of ribbing on the outer surface of the tires which show the exact marking of the areas where the main tire ingredients are (rubber, textile inserts, and metal inserts).

According to Javier Araujo-Morera, Raquel Verdejo, Miguel Angel López-Manchado, Marianella Hernández Santana” These new designs have materialized into innovative products, some of which are already in the market. Airless or non-pneumatic tires that do not deflate under any circumstance use 3-dimensional structures to bear the weight of the vehicle. Goodyear trades airless tires for zero-turn radius mowers, while Michelin offers a line of airless radial tires for construction, recreation, and small-scale utility vehicles. Cooper has been active in the development and evaluation of non-pneumatic tire technology for military use. Another line of innovation and redesign considers self-sealing tires. This technology involves the use of a sealant material placed as an inner layer below the tread. When a puncture occurs, the sealant prevents the loss of air pressure by filling the hole.”
One example is Michelin´ s Tweel tire, an airless integrated tire and wheel assembly, in which the rubber tread is fused to the wheel core with polyurethane rods. The Tweel tire targets performance levels beyond what is possible with conventional pneumatic know-how due to its shear band design, additional suspension, and decreased rolling resistance (Bras and Cobert, 2011). Michelin also introduced Vision, a biodegradable 3D printed smart concept tire, manufactured using sustainable materials. It is airless and equipped with sensors that offer real time updates on the condition of the tire (The International Market Analysis Research and Consulting Group - IMARC Group, 2019). Goodyear has implemented the so-called self-inflating tires, i.e. a sensor/pump combination embedded within the tire structure, which could ultimately eliminate the need for drivers to manually control tire pressure. Another example is the Tire Pressure Monitoring Sensor (TPMS), an electronic device that alerts drivers in case of a tire puncture or under inflation below a threshold (Simonot-Lion and Trinquet, 2017). This feature improves safety, by improving traction, vehicle handling, decreases fuel consumption, increases braking efficiency, reduces tire wear and extends tire lifespan (Kuncoro et al., 2019). Potential applications as sensors by the combination of rigid conductive fillers and flexible and insulating matrices can also be derived from the development of electrically conducting elastomeric compounds (Aguilar-Bolados et al., 2020).

Challenges with Redesign:
According to Javier Araujo-Morera, Raquel Verdejo, Miguel Angel López-Manchado, Marianella Hernández Santana “In an ideal context, the products must be designed, not only based on performance and aesthetics, but also based on other key aspects derived from their subsequent management. They should be designed to be easily repaired, be able to adapt to the new needs of the client, and when they can no longer be useful, they must be simple to be reused in other production processes. When the design of the products considers these concepts, the following links in the chain of the CE will be developed more easily.”

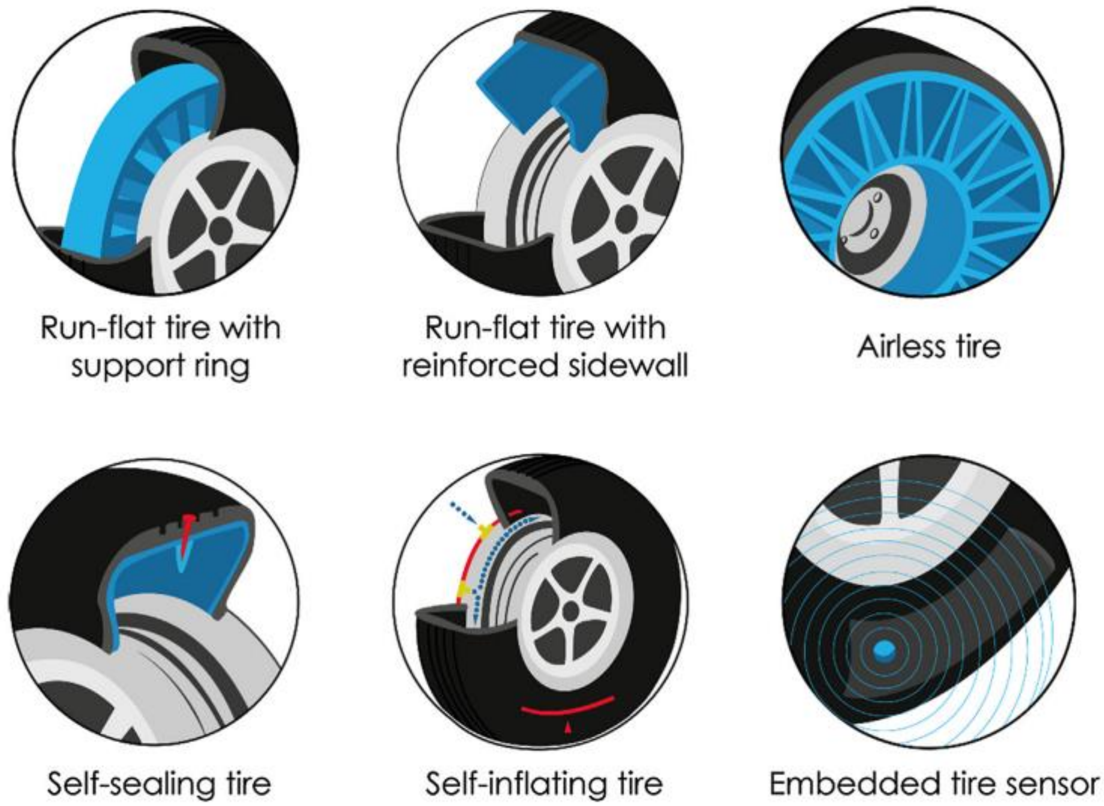


Fig. 3. Innovative tire concepts and designs (Amick, 2018).

3.4.2. Renew

According to Valerie L. Shulman "The combined annual global production of natural and synthetic rubber has grown to approximately 33*106 t (33,000 000 t), of which about 75% is consumed by various divisions of the automotive industries. The preponderance, about 60%, is used for the manufacture of tires for passenger cars, utility vehicles, and commercial trucks. Smaller diverse categories are grouped as 'other,' which include tires for off road vehicles, such as agricultural, civil engineering, industrial, mining, airplane, among others as well as bicycles and motorcycles."

The manufacture of tires from renewable resources is a clear objective to achieve sustainability and reduce the dependency on fossil fuels (Barrera and Cornish, 2015). Natural Rubber has unique reinforcing properties, tear, impact and abrasion resistance, among others. However, the supply of Natural Rubber from Pará rubber tree cannot meet the growing world demand and, thus, new sustainable alternatives are being sought. The two main sources of alternative rubber crops are Russian dandelion (Cherian et al., 2019; Niephaus et al., 2019; RamirezCadavid et al., 2019; van Beilen and Poirier, 2007) and guayule (Cheng et al., 2020; Rasutis et al., 2015; Sproul et al., 2020; van Beilen and Poirier, 2007). Russian dandelion natural rubber (RDNR) shows excellent chemical and physical properties. On the other hand, guayule natural rubber (GNR) has a structural backbone with 99.9% poly(cis-1,4-isoprene) units and analogous molecular weight and physico-mechanical properties to Natural Rubber (Rasutis et al., 2015).

The traditional methods of production of carbon black can be classified into two categories: incomplete combustion and thermal decomposition of hydrocarbons, depending upon the presence or absence of oxygen. However, alternative approaches are now being considered to produce renewable carbon black from biomass products, such as oils and vegetable fats (Peterson et al., 2016; Toth et al., 2018). Peterson et al. (2016) demonstrated the potential to use renewable carbon black (CB) from birchwood biochar in partially replacing CB without any loss of compounds properties.

Challenges with Renew

However, Russian dandelion natural rubber has a potential disadvantage since it contains more associated proteins that can lead to allergic reactions, limiting its use to non-medical applications. Where as in Guayule natural rubber also undergoes the same degree of strain-induced crystallization of natural rubber; however, its tensile strength is slightly lower (Mahata et al., 2020). Both NR and GNR are slow-growing crops that take seven and two years to reach maturity, respectively, whereas RDNR is a fast-growing crop, taking only six months. Unfortunately, it is still too expensive to extract or process the rubber from both RDNR and GNR.

3.4.3. Reduce

Reducing consists in the optimal use of materials. Tire industry targets the weight of the tires to reduce their contribution to the total weight of the vehicle (Rodgers et al., 2016). Such weight reduction also achieves another clear objective, fuel saving. Continental tires, branded as EcoPlus + technology, and Firestone's Fuel Fighter technology are focused on reducing rolling resistance while enhancing grip on wet surfaces and improving tread life (Roy et al., 2019). Also, the Beijing Tiancheng Linglong Tire company is working on the development of graphene rubber compounds for fuel efficient tires. The graphene-enhanced tire is stated to be produced with only a few minor process adjustments to ensure an industrial viable product. This tire is claimed to be safe and antistatic, and with low fuel consumption. In addition, its abrasion resistance and thermal conductivity is said to be extremely high (Linglong Tire, 2019). On the other hand, Gratomic is developing graphene-enhanced tires to increase their resistance and reduce friction. The graphene enhanced Gratomic tires are reported to present more than 30% increase in wear resistance over the ''premium tires" from other known trademarks. Tests based on industry standard dynamic mechanical analysis (DMA) showed a significant progress in rolling resistance, indicating more than 30% improvement in fuel economy. Wet and ice braking distances were also improved by 40% (Gratomic, 2020).

3.4.4. Repair & Reuse

Tires cannot be recycled in the same way that aluminum cans are recycled. Recycling tires requires energy to break down the tire, clean, separate it into rubber/carbon/steel components and then reconstitute them into new tires. Reuse in the tire industry involves:

3.4.4.1. Retreading:

This process is similar to the process used in the creation of a new tire, except that it uses only 30–50% of the material that is required for a new tire.

The most critical component of the tire is the tread because it determines the final performance. Also, it is the thickest component of the tire that suffers the most due to abrasive loss. The tread ensures the gripping action between the road surface and the whole tire; thus, after several uses, its thickness is reduced, and a slippery action takes place on the road surface. At this point consumers have to decide whether to replace the deteriorated tire with a new one (normally expensive) or to retread it, which is a less expensive alternative (Sharma, 2013). A tire can be retreaded several times depending on the type and conditions; car tires can be retreaded 2–3 times; light truck tires 4–5 times; heavy truck tires 8–9 times; and aircraft tires up to 14 times (Imbernon and Norvez, 2016a; Sharma, 2013). Retreading is also a way of reusing that generates energy, material and natural resources savings. It is a safe, low-cost, and environmentally friendly solution. According to the article by Wang Qiang "Tire retreading involves The retreaded tire's structure mirrors that of a new tire, with the addition of a buffer rubber layer to enhance durability and heat dissipation. The process components include tread rubber, buffer rubber, and the carcass, composed of wire cord fabric and rubber composite material." According to the C. Sathiskumar, S. Karthikeyan "The new tread is applied instead of removing old thread to the bare casing using specialized tools. This process is similar to the process used in the creation of a new tire, except that it uses only 30–50% of the material that is required for a new tire. The quality testing has proven that retreaded tires are as safe as new ones when properly inspected and retreated."

3.4.4.2. Regeneration of tire rubber:

Self-healing materials have the capability of recovering their initial properties after suffering damage. White et al. (2001) pioneering work demonstrated the basic self-healing phenomena in polymers. Since then, research focused on self-healing materials and, especially, self-healing rubbers has rapidly expanded with new concepts and strategies being developed in academic and industrial laboratories around the world. Self-healing materials are generally grouped according to the healing mechanism into two main categories: extrinsic and intrinsic. In extrinsic self-healing materials, a so-called healing agent is contained in discrete particles (capsules or fibers) embedded into a polymeric matrix and released upon damage. The discrete healing agent is consumed in the healing reaction and, hence, healing is limited to a single event. On the other hand, intrinsic self-healing polymers make use of moieties becoming an inherent part of the material itself. In this case, multiple healing reactions can take place at a given damage site (Hernández Santana et al., 2018a; 2018b).

Challenges in Repair and Reuse:

- **The quality testing has proven that retreaded tires are as safe as new ones when properly inspected and retreated and retreading is a viable option for commercial vehicles. However, retreading passenger vehicle tires is not recommended as the steel belts and sidewalls may be experiencing the effects of aging and environmental wear and may conceal hidden damage. This is common in big trucks and earthmoving vehicles but not in smaller passenger cars. This is common in big trucks and earthmoving vehicles but not in smaller passenger cars. This is common in big trucks and earthmoving vehicles but not in smaller passenger cars. This is common in big trucks and earthmoving vehicles but not in smaller passenger cars. This is common in big trucks and earthmoving vehicles but not in smaller passenger cars. This is common in big trucks and earthmoving vehicles but not in smaller passenger cars. This is common in big trucks and earthmoving vehicles but not in smaller passenger cars. This is common in big trucks and earthmoving vehicles but not in smaller passenger cars. This is common in big trucks and earthmoving vehicles but not in smaller passenger cars. This is common in big trucks and earthmoving vehicles but not in smaller passenger cars.**
- **Achieving intrinsic self-healing in rubbers is challenging due to crosslinks restricting the formation of new bonds (*Nie et al., 2019)***
- **Although this field of research is growing and getting attention worldwide, self-healing rubbers are still far from acceptable to be used in the tire industry, due to their low mechanical strength. Adding reinforcing fillers and/or combining different healing strategies (Utrera-Barrios et al., 2020a; 2020b) is seen as the path to follow for improving the overall mechanical performance of self-healing rubbers without compromising their repair capability (Imbernon and Norvez, 2016b; Sattar et al., 2019).**

3.4.5. Recover

According to World Business Council for Sustainable Development "Lower cost: The cost of Tires Derived Fuel (TDF) is significantly lower than that of fossil fuels such as natural gas, coal and petroleum coke, especially when exploration, development and transport costs of virgin materials are taken into account. Provided that quality and supply can be maintained, users can incorporate TDF into long-term planning such that significant economic advantages can be obtained." According to World Business Council for Sustainable Development "TDF can be a good use for stockpiles of contaminated tires covered in dirt and water. These tires cannot generally be used for ground rubber and so TDF or construction projects are better options." Energy and material recovery provide a complementary alternative to address tire waste issues. Pyrolysis, gasification, and incineration are thermo-chemical conversion technologies that transform scrap tires into valuable chemical products, fuels, and power (Myhre et al., 2012; S´lusarczyk et al., 2016). These techniques are particularly useful for ELT, and do not depend on the quality or type of tire (Li et al., 2010; Martínez et al., 2013). The Environmental Protection Agency recognizes that "the use of tire-derived fuels is a viable alternative to the use of fossil fuels and The Environmental Protection Agency testing shows that TDF has a higher BTU (British Thermal Unit) value than coal."

3.4.5.1. The incineration

Incineration is the oxidation of combustible material to give inert waste. It is a highly exothermic and spontaneous process that starts at controlled high temperatures (1000 C) and, once initiated, it becomes self-supporting (Forrest, 2014; Myhre et al., 2012). This process produces H_2O, O_2, CO_2 and several toxic gases; although the use of high enough temperatures can avoid the formation some of these toxic components, such as dioxin. Incineration is often carried out by the tire industry to dispose of production waste and rejects, and to produce their own energy. According to C. Sathiskumar, S. Karthikeyan "Combustion process directly uses waste tires as fuels in incinerators because of its high calorific value and is an excellent material for energy recovery. The reduced power production cost, maximum heat recovery, and environmentally acceptable process are the advantage of a combustion process. The demerits of the combustion process are no material recovery, capital investment is high, the need for flue gas cleaning, emission of CO_2 gas and operating cost is high [12]. Waste tires can be used as fuels in cement kilns."

3.4.5.2. Gasification

Gasification is a partial oxidation process that uses pressure, heat, and a reactive agent (air, oxygen, hydrogen, or steam) to convert tire waste into a gas mixture primarily composed of CO and H_2, with a low calorific value (5–6 MJ Nm3) (Ramos et al., 2010), along with CO_2 and light hydrocarbons (CH_4), also known as synthesis gas or syngas. Syngas is dependent on the operating conditions and the concentration of the oxidizing agent. It is used as fuel in fuel cells or gas turbines to obtain a wide range of other fuels and chemicals (Manoharan and Naskar, 2019; S´lusarczyk et al., 2016).

3.4.5.3. Pyrolysis:

Pyrolysis consists in the thermo-chemical decomposition (400– 1200 C) of organic compounds into low molecular weight products at reduced or normal pressure and under an inert atmosphere, preventing oxidation and changes of phase or chemical composition (Bockstal et al., 2019; Forrest, 2014; Imbernon and Norvez, 2016a; Mavukwana and Sempuga, 2020). According to the Li W, Huang CF, Li DP "using pyrolysis as a recovery method has been widely researched since it results in reduced secondary pollution of the environment and the potential for the higher economic value of products. The pyrolysis process degrades the organic components of waste tires to obtain gases, condensable oil, and solid char." According to the Ahmed Akbas and Nor Yuliana Yuhana "This section focuses on how rubber waste converted to secondary oil fuel has the same capability of the fuel itself through a process called pyrolysis. This technique for recycling adopts heat (>400 ◦C) for shredding tires in a reactor container under oxygen-free conditions. Moreover, it is an alternative method dealing with vulcanized rubber to recover a useful product." According to the Wang F, Gao N, Quan C "Pyrolysis technology has developed and matured enough over time to be regarded as a rapid and efficient treatment option to solve the environmental problems caused by waste tires. The steel, rubber, carbon black, additives, and other materials contained in the waste tire may be recovered and almost no waste by-products are produced from the pyrolysis process" According to the C. Sathiskumar, S. Karthikeyan "Pyrolysis process is a thermal decomposition of the waste tire in an oxygen-free environment. Waste tires can be thermally decomposed at 400 °C. The product of the pyrolysis process is tire pyrolysis oil, pyro-gases, and pyro-char."

3.4.5.3.1. Pyro char

According to Ningbo Gao , Fengchao Wang, Cui Quan, Laura Santamaria, Gartzen Lopez, Paul T. Williams "Pyro char has been explored for applications in energy storage devices, specifically in batteries and capacitors. The unique properties of tire char, such as high specific surface area and conductivity, make it a potential electrode material for supercapacitors and batteries. Activated tire char has demonstrated good electrochemical properties, making it suitable for supercapacitor applications. The low cost of using waste tires for processing tire char makes it an economically viable option for energy storage materials." According to Z. Liu, Q. Yu, Y. Zhao "Pyro-char has very high carbon content which can be a low cost and waste precursor to synthesize porous activated carbon

material which can be further used in energy storage devices." According to C. Sathiskumar, S. Karthikeyan "Recently pyro char has been used to obtain electrode materials for Li, K, Na-ion battery, supercapacitor, and electrocatalyst (ORR). Tire-derived activated carbon has numerous advantages such as high surface area with porosity, high electrical conductivity, and delocalized π electrons. This work opens a new avenue for waste tire recycling and uses in electrochemical applications including energy storage devices."

3.4.5.3.2. Pyro gas

According to the K. Srilatha, D. Bhagawan, S. Shiva Kumar, V. Himabindu, "The gas-phase products from waste tire pyrolysis generally are a mixture of olefins, carbon oxides, hydrogen and a small amount of sulfur and nitrogen compounds. Hydrogen is considered as an efficient and environmentally friendly fuel over fossil fuels due to its high energy density, carbon-free energy, and zero greenhouse gas emission. There is much interest in the use of alternative precursor for the production of hydrogen, particularly the use of waste materials."

3.4.5.3.3. Pyrolysis oil (TPO)

"TPO can be used as an alternative fuel in the engine. Pyro-gas can be used as fuel in the pyrolysis process and the maximum content in the gas in hydrogen." According to P.T. Williams, "TPO contains valuable chemicals such as benzene, toluene, xylene, limonene, and styrene, making it suitable for applications in the chemical industry." According to P. Verma, A. Zare, M. Jafari, T.A. Bodisco, T. Rainey, Z.D. Ristovski, J.B. Richard, "Distilled TPO, when compared to diesel, shows potential as a fuel. However, challenges include higher emissions of CO and CO2 due to TPO's higher density and viscosity. TPO can be used directly as fuel in boilers and internal combustion engines after specific modifications, including sulfur reduction, moisture removal, and distillation." The crude tire pyrolysis oil (TPO) obtained by this process had a higher viscosity and also higher sulfur content compared to diesel fuel.

3.4.5.4. Co-processing in thermoelectric power stations:

In this process, ground tires are used with coal in the combustion reactor section to produce electrical energy and thermal energy. Tires generate 25–30% more energy than traditional power stations. Moreover, CO2 emissions are also reduced by around 23%

3.4.5.5. Steel fibers from tire waste:

According to S.M Samindi M.K Samarakoon, Pal Rubena Jorgen Wie Pedersen, Luis Evangelista "Steel fibers from tire waste, when used to reinforce concrete, offer an environmentally friendly and economically viable way to manage recycled tire products. The study focuses on comparing the mechanical properties of recycled fiber-reinforced concrete (RFRC) with manufactured fiber-reinforced concrete (SFRC). The research explores the potential of using steel fibers recovered from tire waste as an alternative building material to manufactured steel fibers."

Challenges

- **The volume reduction of waste by more than 90% and net energy recovery with possible material recovery are the main advantages of these methods. However, generation of toxic gases, disposal of ashes, and so forth are some problems associated with these thermal treatments (Manoharan and Naskar, 2019).**
- **The demerits of the combustion process are no material recovery, capital investment is high, the need for flue gas cleaning, emission of CO2 gas and operating cost is high.**
- **Pyrolysis is less frequently used worldwide than incineration for obtaining energy due to non-competitive prices, low quality of the obtained products, high operation and maintenance costs, and the absence of a wide market for consumption of the obtained products.**
- **Achieving uniformity and consistency in the properties of activated carbon derived from tire char remains a challenge. Variations in feedstock composition, pyrolysis conditions, and activation processes can result in diverse characteristics of the final activated carbon.**

- **Tailoring the properties of activated carbon for specific applications is crucial. Understanding the requirements of diverse applications, such as adsorbents, batteries, supercapacitors, and catalysts, can guide the optimization of activated carbon properties to maximize performance.**

3.4.6. Recycle

Recycling, as defined by the Parliament and Council of the EU (European Parliament, 2008) is any recovery operation whereby waste materials are reprocessed into substances, materials or products, either for the original or other purposes. Fortunately, the EPA estimates there are more than 110+ different products that can be made from recycled tires. In addition, scrap tires can be used in their original form without any physical or chemical treatment for simple and economical applications such as insulation for the foundations of buildings, art projects, protective barriers along roads and highways, playground equipment, and artificial reefs. Instead, most used tires are recycled for use in athletics tracks and manufacturing plants.

The first step in any tire recycling route must consider the production of crumbs from scrap tires. Using the whole tire as starting material has disadvantages over tread buffing, due to the presence of either fabric or metal particles, which not only contaminate the product but can also act as stress concentration points resulting in premature tears, breaks and cracks (Forrest, 2014). Therefore, removing fabric and metal, in the most efficient way possible during the recycling process, is very important to ensure the quality of the final product.

According to the Environment Protection Agency had launch U.S. Federal Research Action Plan (FRAP) on recycled tire crumb rubber used on synthetic turf playing fields and playgrounds, specifically focusing on the Tire Crumb Characterization research. There are 12,000-13,000 synthetic turf fields in the U.S., with 1,200-1,500 new installations each year. Most fields use tire crumb rubber as infill material, sometimes mixed with sand.

According to World Business Council for Sustainable Development "Whole or shredded tires are successfully used in a variety of civil engineering projects such as embankments, backfill for walls, road insulation, field drains, erosion control/rainwater runoff barriers, wetlands and marsh establishment, crash barriers and jetty bumpers. Tires are excellent materials for such uses because they are lightweight, permeable, good insulators, shock absorbent, noise absorbent and durable."

Ground tire rubber (GTR):

It can be used in the manufacture of ground covers in playgrounds, lower layers of floor coverings, walkway tiles, mulch for agricultural purposes, landscape applications and sports surfaces such as running or jogging tracks. Moreover, compounds containing GTR can make up a variety of rubber products, such as conveyor belts, tubes, molded and extruded profiles, shoe soles and heels, car mats, mattresses, sealing plates, battery boxes and other hard rubber goods (Mishra et al., 2019; Rodgers and D'cruz, 2015). The use of GTR in the cement and concrete industry is another area of research that has been developed considerably in the last decades (Forrest, 2014; Rodgers and D'cruz, 2015; Thomas and Gupta, 2015; Youssf et al., 2016). The elasticity given by GTR improves fracture resistance, lowers density, favors heat and sound insulating and energy absorption properties, and reduces cracking and vibration transmission. The asphalt industry also uses GTR as filler for road surface treatment. Blending GTR with asphalt has advantages in the performance of roads and their longevity as it reduces the noise of the vehicles traveling on it, improves crack and skid resistance, and provides a more comfortable ride (Hallmark-Haack et al., 2019; Shu and Huang, 2014; Wu et al., 2016)

Reclaim/Devulcanization:

Reclaiming involves disrupting the original three-dimensional rubber network to decrease molecular weight, On the other hand, devulcanization causes the selective breakup of the chemical network. It consists of the cleavage of the intermolecular bonds of the network, such as carbon–sulfur (C-S) and/or sulfur-sulfur (S-S) bonds, that breaks down the macromolecular chains without damaging the backbone network and avoiding material degradation (Sabzekar et al., 2015). Both reclaiming and devulcanization aim to obtain a rubber compound that can be reprocessed and revulcanized like virgin rubber. However, the difficulty to precisely focus on one type of bond rupture and the simultaneous occurrence of both processes hinders the full recovery of the original properties (Sienkiewicz et al., 2017). Thus, reclaimed/devulcanized rubber can only provide a low-cost material to compounds for less demanding products (Isayev, 2013). According to C. Sathiskumar, S. Karthikeyan "Reclaiming of scrap rubber is the breaking of carbon bond while de-vulcanization is the cleavage of sulfur bonds

in the molecular structure. Reclaiming products means the conversion of a threedimensionally interlinked, insoluble and infusible strong thermoset polymer into a two- dimensional, soft plastic, processable and vulcanizable polymer, simulating many of the properties of virgin rubber. Reclaiming of scrap rubber products, e.g. used automobile tires and tubes, hoses, conveyor belts etc., Reclaiming process is of two different types: physical reclaiming processes (mechanical, thermomechanical cryo-mechanical, microwave, and ultrasonic) and chemical reclaiming processes (organic disulfides and mercaptans, inorganic compounds, miscellaneous chemicals, chemical degradation)"

Challenges with Recycle:

- **According to Article by Fabrizio Quadrini, Loredana Santo and Ettore Musacchi "Evaluating the true industrial potential of a recycling technology is a complex undertaking. The direct molding of ground tire rubber (GTR) demonstrated promising material properties at the laboratory scale but transitioning to industrial production presented challenges."**

4. **CASE STUDY: These following case studies exemplify the real-world applications of recycled and repurposed tire materials, demonstrating the feasibility and benefits of circular economy principles in different industries and product categories. They underscore the potential for scrap tire recycling to address environmental concerns and create economic opportunities.**

Case Study 1: Waste Tire Management: Lebanon Case Study by Mrad M and El-Samra

Lebanon currently faces a massive and growing waste tire problem, with over 2 million scrap car, bus and truck tires generated per year (Mrad & El-Samra, 2020). This is expected to keep increasing with vehicle ownership rising sharply. Unregulated dumping of these waste tires in open unsanitary sites is creating major disease, fire, groundwater contamination and air pollution hazards (Mrad & El-Samra, 2020). As an urgent public health and ecological issue, sustainable management strategies for scrap tires need implementing at the national level. Specific statistics for Lebanon's vehicles and scrap tires generated are: 1.9 million registered vehicles in 2017, over 2 million tires wasted annually, projected vehicle numbers could reach 9 million by 2035 with waste tire volumes scaling correspondingly (Mrad & El-Samra, 2020). Open dumping poses unacceptable environmental and health risks that need addressing through systematic recycling and reuse. The Mrad & El-Samra (2020) case study analyzes three scrap tire recycling alternatives for feasibility in Lebanon - retreading, shredding and pyrolysis recycling. It finds tire retreading to be a low cost, environment friendly option that reuses old tire casings to extend product lifetimes. However, negative public perceptions about quality currently limit adoption locally (Mrad & El-Samra, 2020). Tire shredding and pyrolysis can process a high volumes but require large machinery investments of $0.73-$3 million (Mrad & El-Samra, 2020). Though economically viable in the longer term after markets develop. Integrated national strategy is recommended across municipalities for collection, storage plus retreading, shredding and reuse facilities for construction material (Mrad & El-Samra, 2020).

Case Study 2: Analysis of recycled tire rubber modified bitumen in Albania for quality of the road construction by K Dhoska

Waste tire dumping has become a crucial environmental and public health issue in Albania, with tire recycling emerging as a vital industry over the past decade to manage this problem (Dhoska et al., 2019). The present case study explores the technique of modifying standard bitumen with 10% recycled tire rubber by weight, to produce rubber-modified bitumen (RMB) for road construction applications. It studies RMB's physical and mechanical properties through extensive lab testing. Penetration and softening point testing showed over 16% reduction in penetration depth - from 73mm in standard bitumen to 61mm in RMB, along with 16% increase in softening point temperature - from 49°C to 57°C with rubber modification (Dhoska et al., 2019). This indicates enhanced viscosity and suitability for road-building in hot climates. Additionally, Marshall stability measurements met relevant industrial standards for properly compacted RMB samples. Long-term testing over 10 years found up to 3 times lower cracking incidence in roads laid with RMB compared to conventional bitumen (Dhoska et al., 2019). The improved physical properties and real-world cracking resistance conclusively prove that using recycled tire rubber particles to modify bitumen can simultaneously enhance road quality and

lifespan in Albania, while providing an eco-friendly route to manage the country's mounting waste tire stocks. Hence, the study strongly advocates adopting this sustainable technique nationwide for effective solid waste management and superior road infrastructure.

Case Study 3: Students in remote areas enjoy basketball court made of recycled tires Source: Xinhua

Meituan, a Chinese technology company, has taken a proactive stance in addressing the environmental impact of shared bikes and electric bicycles by repurposing more than 2,000 discarded tires into a basketball court for Nihanzhen Lishu Center Primary School in Guizhou province. Launched on June 5, 2020, as part of a nationwide initiative, the program has already donated 19 similar sites across China, recycling approximately 42,000 tires. The innovative approach not only tackles the challenge of tire disposal but also provides a sustainable and recreational solution for children in remote mountainous areas. By focusing on an environmentally peaceful method of recycling, Meituan aims to contribute to waste management and promote a circular economy. This case study highlights how companies can integrate sustainability into their corporate initiatives, addressing specific challenges in the lifecycle of common products and fostering community well-being.
Citation: Information and quotes provided by Meituan staff member Qin Hao.

5. Environmental Impact Assessment

According to Kurt Reschner "When referring to incineration, some people use the term "energy recovery" or even "thermal recycling". While this sounds more impressive that "incineration" or "burning", the fact remains that the use of a material for its originally intended purpose more preferable, both from an environmental and from an economic standpoint. This becomes obvious when we take a closer look at the typical energy consumption to produce tire rubber and compare it to the energy gained by burning a tire:
Table 3:

Energy needed to manufacture a tire	**32,0 kWh/kg**
Energy needed to produce tire rubber compound	**25,0 kWh/kg**
Thermal energy released when incinerating scrap tires	**9,0 kWh/kg**
Energy consumed in the process of grinding scrap tires into crumb rubber (0.5 to 1,5 mm)	**1,2 kWh/kg**

Table 3: it takes 3 – 4 times as much energy to produce tire rubber, compared to the energy recovered by "thermal recycling". Consequently, the use of recycled tire rubber for its originally intended (or related) purpose makes by far more sense than incineration, both environmentally and economically. Specific energy values."
Sources: compilation by Kurt Reschner

6. Global Tire Recycling Market Synopsis

According to Valerie L. Shulman "**Tires are an essential part of the economy of every country that relies upon vehicular and/or air transport to move people and goods." This is supported by reports from the United Nations Environment Programme (UNEP) and the World Bank, which state that "the Global tire recycling rate is only around 20%. Furthermore, the increasing cost of disposing tires has pushed many countries to invest in tire recycling as an alternative." According to the Adroit Market Research, "The global tire recycling market is appraised to have a market size of USD 4,600.28 million by 2028 with and annual CAGR rate of 3.41% from 2021 to 2028. The Global Tire Recycling Market is projected to grow at a CAGR of 5.2% from 2019 to 2026, reaching a market value of US$8.67 billion by the end of 2026. The key drivers behind the growth of this Global Tire Recycling Market are the increasing awareness and concern about the environment, rising tire disposal costs, and the availability of advanced technologies for tire recycling. In addition, rising income levels in developing countries will make vehicles more accessible, further increasing tire sales in those markets in the upcoming years (The Freedonia Group, 2018). Such global market creates a significant annual demand for tire replacement and, thus, generates a great number of end-of-life tires (ELT) Recycling old tires to new ones is not cost-effective considering the high rate of energy required to break down the tire, clean it up and then reconstitute it into a new tire.**

	Millions of ELTs generated per year (excluding export and retread)	Of those tires that do not go to export or retread, they are destined for: Energy recovery (%)	Civil engineering uses or material recovery (%)	Landfill, stockpiled, discarded waste or other (%)	Specific reuse/ disposal/ recovery data not available	Year	Sources
USA	**292**	53	33	14	n/a	2005	Estimates based on data from Rubber Manufacturers Association (RMA)
Europe	**250**	41	43	16	n/a	2006	Estimates based on data from European Tyre & Rubber Manufacturers' Association (ETRMA) Europe (EU 27 plus Norway and Switzerland)
China	**112**	n/a	n/a	n/a	100		Various newspaper articles including Recycling Today and Hong Kong Trade Development Council
Japan	**80**	70	15	15	n/a	2006	Estimates based on data from Japan Automobile Tyre Manufacturers Association Inc. (JATMA)
Mexico	**30**	0	90	10	n/a	2004	"Mexico pays cement industry to burn scrap tires" www.ecoamericas.comm/en/story/.aspx?id=569
Brazil	**27**	69	13	18	n/a		Associação Nacional da Indústria de Pneumáticos (ANIP), Instituto Brasileiro de Geografia e Estatística (IBGE)
South Korea	**23**	77	16	7	n/a	2003	Korea Tire Manufacturers Association (KOTMA)
Canada	**22**	20	75	5	n/a	2003	Pehlken A. and E. Essadiqi, Scrap Tire Recycling in Canada, 2005.
Australia	**20**	22	8	70	n/a	2006	URS, Market Failure in End-of-life Tyre Disposal, report for the Department of Environment and Heritage, September 2006 (see also www.environment.gov.au/settlements/waste/tyres/index.html).
Malaysia	**14**	n/a	n/a	n/a	100		What to do with old tires? Lim J.
South Africa	**12**	n/a	n/a	n/a	100	2003	"Fixing a Tyred Environment", Die Burger, 6 April 2003
Iran	**10**	n/a	n/a	n/a	100	2006	Iran daily newspaper online (/www.iran-daily.com/1385/2586/html/focus.htm)
Israel	**7**	n/a	n/a	n/a	100	2003	Ministry of the Environment, Israel "Waste Tires : A Case Study", Environmental e-bulletin September 2003, Issue 2 (see also www.sviva.gov.il)
New Zealand	**4**	0	15	85	n/a		Estimates taken from "Product Stewardship Case Study for End-of-Life-Tyres" by URS for the Ministry of the Environment (NZ) 2006

For USA, Europe and Japan, ELTs destined for export and/or retread are excluded from the volume of ELTs generated per year.

According to World Business Council for Sustainable Development

1) **Tire Recycling Market by Players**
2) **Global Rubber**
3) **L&S Tire**
4) **Champlin**
5) **Golden By-Products**
6) **Mac's Tire Recyclers**
7) **Tire Disposal & Recycling**
8) **Emanuel Tire**
9) **Entech**
10) **Lakin General**
11) **Liberty Tire Services**

7. Future Outlook and Recommendations

- **According to** Kurt Reschner **"A variation of landfilling is monofilling, which means that scrap tires are not mixed with other waste materials, but stored at a dedicated, licensed location. Once the monofill has reached its capacity, it is covered like any other landfill to reduce the fire hazard and also prevent mosquito breeding."**

- **According to World Business Council for Sustainable Development " Tire manufacturer programs play a key role in the development of ELT markets, as do government regulations, business norms, and standards. ELTs should be considered as a resource and not labeled as a waste. The involvement of tire companies, ELT management companies, scientific laboratories, government regulators and industrial partners is necessary in research and development programs to find new, effective and environmentally sound uses for ELTs."**

- **Next time you need to replace your customers' old tires, make a point to recycle them. If you don't have plans to turn them into something new at your business, find a company in your area that specializes in recycling tires. This way, you can do your part to protect the environment and your**

community while ensuring your organization is fully compliant with federal, state and local requirements. The next time you are to replace your car tires, make it a point to recycle them. Those tires may be used as a planter in your yard. If you can't think of a way to recycle tires, you can take them to a local tire retailer or contact your city's waste management office.

- **According to the article by Wang Qiang "Low Consumer Awareness: Many consumers, especially private car owners, lack awareness and have safety concerns regarding retreaded tires. Some perceive retreaded tires as risky, leading to a reluctance to use them."**

- **According to the article by Wang Qiang "Lack of Policies and Support Mechanisms: The state's insufficient attention to tire retreading results in a lack of supportive policies, regulations, and financial aid. Some retreading enterprises face challenges in development due to a lack of policy support and capital for equipment renewal."**

- **Joint actions and cooperation between industries, scientists, and government regulatory institutions are crucial. Scientific collaboration can establish research and development programs, leading to tire circularity and addressing public concerns about tire environmental impact.**

- **Main tire industries should expand the use of renewable materials, develop innovative solutions, and invest in groundbreaking technologies. Companies like Bridgestone and Michelin have set ambitious goals for using sustainable materials and achieving full tire recycling.**

8. Conclusion:

In conclusion, an effective end-of-life tire management is paramount to safeguarding the environment, public health, and unlocking economic potential through material recovery and reuse. With an annual global generation of over one billion scrap tires, embracing sustainable practices grounded in circular economy principles can turn tire waste from an environmental liability into a valuable asset.

This study highlights the critical need for comprehensive strategies, policy frameworks, innovative technologies, and collaborative efforts among stakeholders to address scrap tires sustainably. Shifting from a linear take-make-dispose model necessitates rethinking tire design, production, usage, and end-of-life stages, employing the 7Rs: reduce, reuse, recycle, redesign, repair, recover, and renew. Solutions span the entire value chain—from renewable materials and smart tire construction to devulcanization for regeneration and pyrolysis for material upcycling. Concurrently, economic incentives, infrastructure investments, and heightened consumer awareness can drive the adoption of circular approaches.

Practical implementations demonstrate the viability and benefits of sustainable tire recycling, illustrated through case studies such as rubber-modified bitumen for improved road quality and the creation of community basketball courts from recycled tires. However, effectively managing the substantial volumes of scrap tires requires a coordinated, global initiative. Through collaborative efforts involving industry leaders, policymakers, and environmental groups guided by circular economy principles, the tire challenge can be reframed as an opportunity for sustainability and economic growth. This research emphasizes the urgent need to transition toward tire production and consumption systems that are recyclable, reusable, and renewable for a more sustainable future..

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